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Recent Work on the Georgia Tech High School Field Mill Project

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Abstract

The Georgia Tech High School Field Mill Project is an outreach effort sponsored by the Severe Storms Research Center (SSRC) at the Georgia Tech Research Institute (GTRI). The aim of the program is to develop an accurate, low cost atmospheric electric field mill which capable high school students can build, calibrate and operate.

An atmospheric electric field mill is a device designed to measure the magnitude and polarity of the vertical electric field in the atmosphere. The measurements are typically made by alternatingly exposing and shielding conductive plates from the atmospheric field. The induced charge on the plates can produce a current across a resistance to ground. This alternating current can be measured to infer the value of the vertical field. The eventual goal of the program is to deploy a network of these sensors across the state of Georgia. By linking the mills, and associating mill output with local weather conditions, it is hoped to allow the students to participate in future lightning and thunderstorm research projects.

This paper will present a short history of the program, with the contributions of five individual students explained. The evolution of the field mill design will be described. The current design of the mill, the methods used to calibrate it, and some recent results will be presented.

Introduction

The SSRC was established to investigate severe local storms in the state of Georgia and to investigate methods of better detecting and predicting those storms. Another aim of the SSRC is to enhance scientific outreach in the area of severe storm awareness and research to students in the state of Georgia.

The Georgia Tech High School Field Mill Project has been developed from a mentoring program between local high schools and the SSRC. In the program, high school students from a local magnet high school are mentored over the course of a semester. The goal of the program is to involve the students in some 'real world' science and have them, in a very self-directed manner, produce reportable scientific progress in a presentation setting by the end of the semester.

The development of an atmospheric electric field mill was chosen as a trial project for several reasons. The deployment of an inexpensive array of field mills is an element in a long range goal of the SSRC to investigate lightning initiation and cessation prediction methods. To that end, there are numerous plans in various media that describe relatively simple plans for the construction of field mills [Carlson, 1999] [Chubb, 2007] [Kneifel, 2005] [Trostel, 1983].The details of these plans are generally on the level that can be accomplished by well mentored high school students. The SSRC also already operates a commercial field mill and therefore has a 'gold standard' against which the student mill may be compared.

Over the last few years, a total of five students have been involved in the construction, evaluation and refinement of the field mill. Initial potential plans were identified and an ‘alpha’ version of the ‘student field mill’ was produced by the first mentee. The alpha version was compared with a commercial field mill, the Vaisala EFM-II. After analysis of the results of this initial comparison, the second student made some incremental improvements to the student mill electronics.

A third student transitioned the alpha version of the student mill from handcrafted printed circuit boards (PCBs) to a beta version using ‘professionally’ laid out boards. Another aspect of this students work was the development of methods to both calibrate response and measure enhancement factors for field mills. This third student also performed a side by side comparison of the improved student mill with the EFM-II.

The fourth and fifth students were involved in the construction and intercomparison of multiple, “mass produced” student field mills.

Development of the Initial Alpha Prototype

The first student involved in the project was charged with finding a simple, yet effective design of an atmospheric electric field mill, within the capabilities of an advanced high school student to build. The design also needed to be relatively inexpensive. The plan chosen was from a German hobbyist website [Kneifel, 2005]. The main components of the alpha version of the student mill were constructed from six handmade PCBs fastened together with three bolts and a circuit hand wired on a piece of 'perf' board, all fit inside a small coffee can. The coffee can enclosure provides both physical and electrostatic shielding for the electronics within. The main sensing elements of the alpha mill consist of a circular plate divided into four conductive quadrants. The two opposing quadrants are wired together and insulated from the other pair of quadrants. Above the sensing element, a single conductive, grounded 'chopper blade' is attached to a small DC motor. The arrangement of the sensing elements and the chopper blade can be seen in Figure 1. As the chopper blade spins above the sensing elements, alternating positive and negative charges are induced on the commonly wired sensing elements due to the ambient electric field.

Below the sensing elements PCB is a small replica of the upper chopper blade. This lower chopper interrupts the signal through an optical coupler and, by this means, allows the position of the upper chopper blade to be known and the AC signal from the sensing elements to be rectified and the magnitude and sign of the field to be determined.

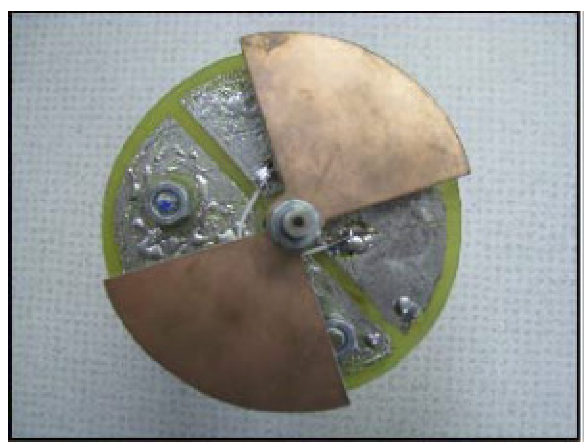

Figure 1. Top view of alpha Version of the field mill showing the chopper blade and the sensing elements.

Figure 2 shows a side view of the assembled alpha mill, showing the four handmade PCBs and the chopper blade held together with standard nuts and bolts. The motor which spins the grounded chopper blade can be seen mounted between the second and third PCBs.

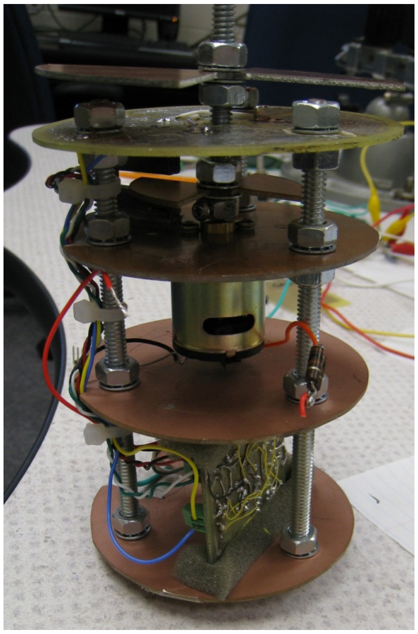

Figure 2. Side view of alpha mill

Figure 3 shows the completed alpha mill mounted inside a standard coffee can, ready for deployment. The mill can be run for days off a small motorcycle battery. Total material costs of the first version of the mill were about $90.

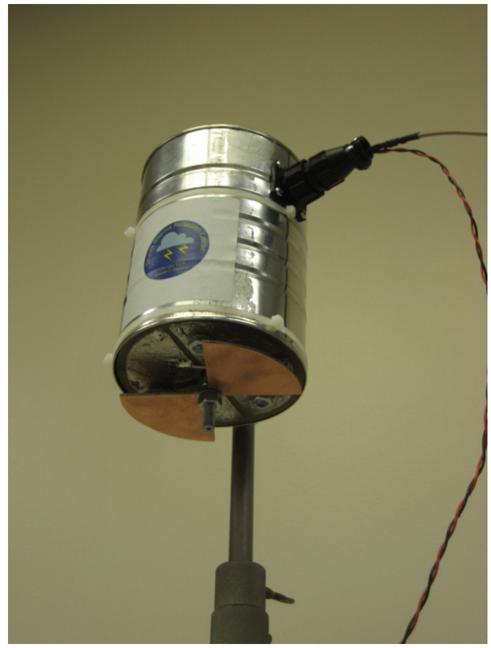

Figure 3. Alpha mill deployed in coffee can container

The alpha version of the mill run alongside a commercial field mill, the Vaisala EFM-II. The results of this side-by-side comparison are presented below in Figure 4. The uncalibrated high school mill output was compared to the Vaisala results by adding a linear offset and a constant multiplicative scale factor. This assumes that a standard linear calibration is valid for these data.

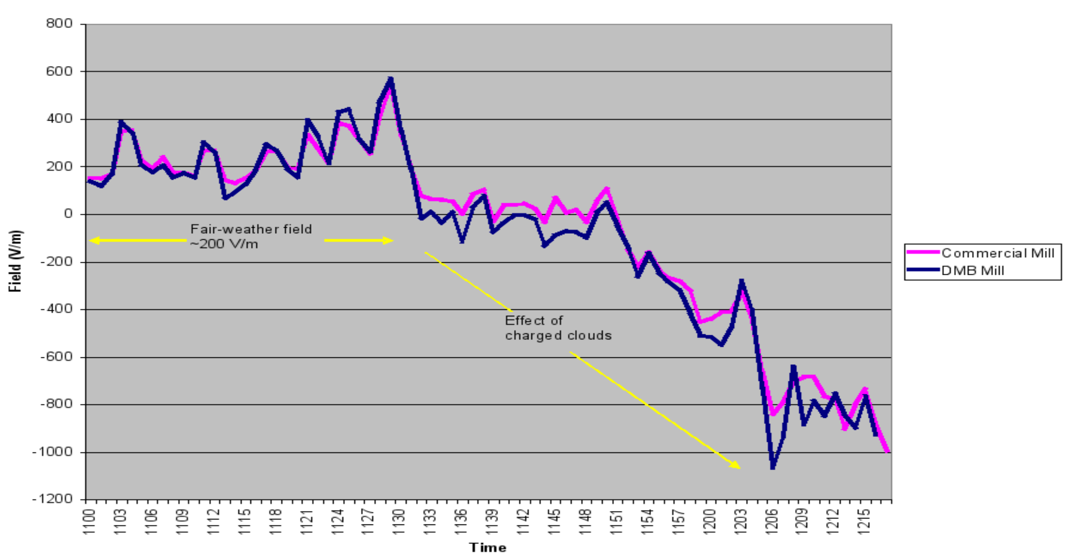

Figure 4. Side-by-side comparison of alpha student mill (DMB Mill) with commercial (Vaisala) mill

Alpha Version - Motor Control & Calibration

The second student involved as a mentee was charged with improving the performance of the mill and with performing calibration of the mill.

One issue the student tackled was the rotation rate of the mill. The slow depletion of the 12V battery driving the chopper motor lead to a non-constant rotation rate and inaccurate data. The student's solution to this problem was to include a 6V voltage regular in the motor power supply, providing a constant voltage to the motor and stability to it's speed.

The initial calibration of the mill was conducted using two 10 foot square conducting plates, illustrated in Figure 5, below. The top plate was charged, using a power supply, to a known voltage, while the bottom plate remained grounded. This produced a very uniform electric field between the plates. A small circular hole was made in the bottom plate which allowed the mill to be placed with the sensing elements flush with the grounding plates.

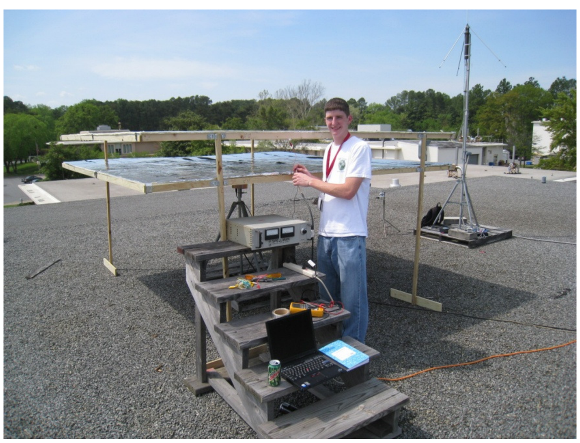

Figure 5. Calibration using 10' conducting plates

With a plate separation of about 0.3 meters, induced fields between $+10kVm^{-1}$ and $-10kVm^{-1}$ were produced. Results of these calibrations showed that the response of the mill to large field values was quite linear. An examination of the response of the mill to smaller, fair weather field values, on the order of +/- 100 Vm^{-1} showed a problem in which the calibration was not single valued between +/- 75 Vm^{-1}.

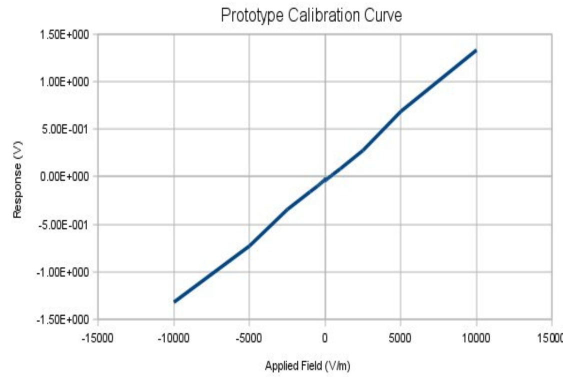

Figure 6. Linear calibration at high field values for alpha mill

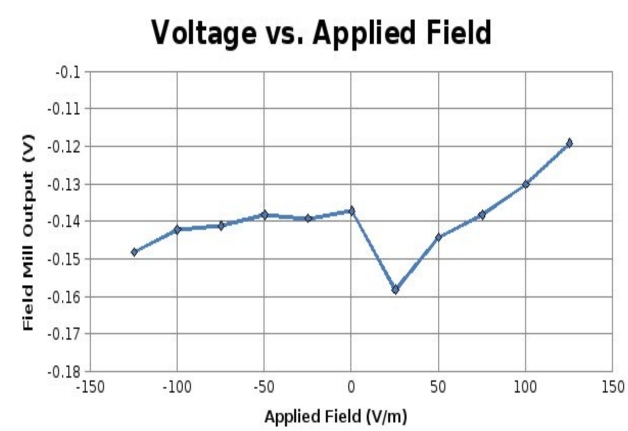

Figure 7. Non single-valued calibration at 'fair weather' values for alpha mill

First Beta Version

The third student mentee used the Altium® printed circuit board (PCB) design program and Pspice® circuit simulations to layout and optimize the design developed by the first two students. The original hand-made, alpha version of the mill, a cardboard mock-up of the Atlium® designed PCBs, and a completed beta version field mill are shown in Figure 8. The total cost of the more "professional" beta version was about $200, but should be less for mass-produced units.

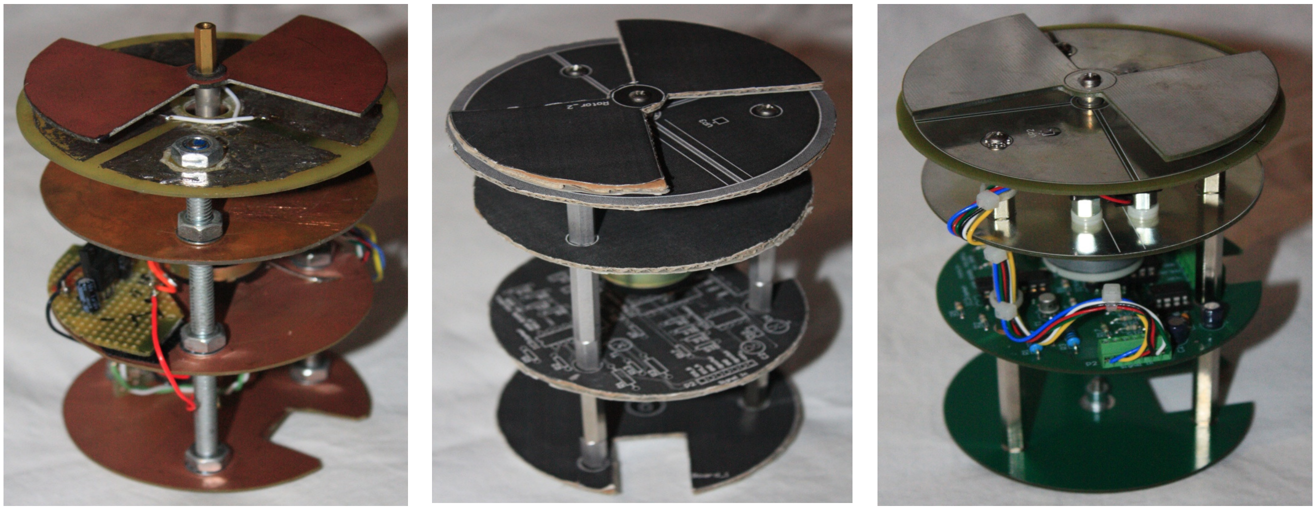

Figure 8. Comparison of hand-made alpha mill, cardboard mock-up, and "professionally" designed beta mill

Additional Modifications and Improvements

Several modifications to the beta mill design were made on the basis of discussions with colleagues and from observations of the performance of the mills over time.

The initial design used a pair of voltage op-amp circuits, one for each set of diametrically opposed sensor quadrants. This design was modified to use more stable charge op-amp circuitry.

A second modification has involved the treatment of the chopper plate axle penetration through the sensor plate. In the initial design, the axle was simply placed through a hole in the sensor plate. The axle tended to rub the sides of this hole, resulting in non-constant rotation rates. The bare axle was initially treated by enclosing it in a low-friction sleeve which was then anchored to the sensor plate. Oiling of the sleeve was required in order to maintain the low friction in this sleeve. The mill design now employs a bearing fitted to the chopper blade shaft, which is secured to the sensor plate. This has proved to be a superior design.

Improved Calibration

The calibration setup and procedure has also been improved. The calibration is still accomplished using two parallel conductive plates. In the improved calibrator design, the plates have been made out of rigid construction insulation board. This allows the plates to be made much smaller, only one meter square. The plates are also placed at a firmly fixed separation of 10 cm. This setup has proved simple, reliable and repeatable.

High and low field calibration results are shown in Figures 9 and 10, respectively.

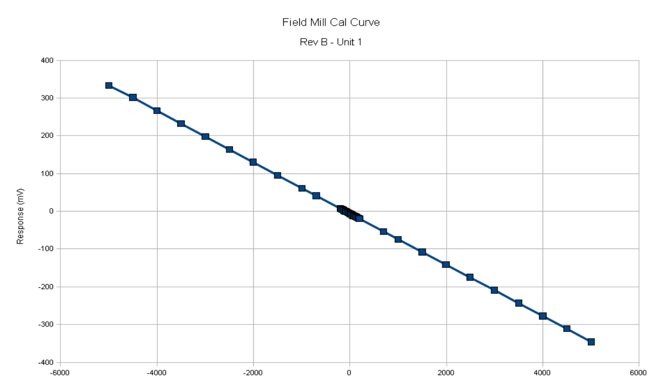

Figure 9. High field calibration using simplified plates

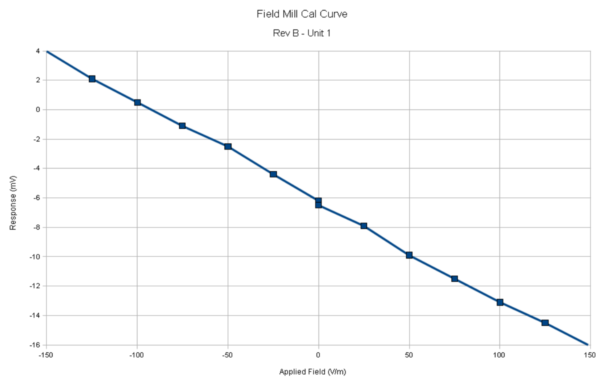

Figure 10. Low field calibration using simplified plates

Production of Multiple Mills

The fourth student, employed over the summer of 2011, condcucted a low-rate production run of the beta version of the student mill. The student assembled and tested four additional beta mills. This resulted in a stockpile of 5 beta mills available for testing

Evaluation of Multiple Mill

The most recent student was charged with comparing the operation of the five beta mills to determine if they were similar enough to be used simultaneously in various tests to investigate long-term stability of the mill design, to determine the effects of orientation on mill output, and to compare with the commercial mill.

8.1 **Stability Tests**

The first tests performed by this student were designed to look at the stability of the mills. When exposed to a constant field, each mill should produce stable and constant output. A recording of mill output versus time for all five mills is shown in Figure 11.

Stability Tests by Hand										
Rev B	1		2		3		4		5	
Time	0V	100V	0V	100V	0V	100V	0V	100V	0V	100V
0	-.044	-.139	.005	-.041	-.532	-1.031	.013	-.097	.009	-.086
1	-.049	-.154	.005	-.042	-.471	-1.024	.017	-.099	.011	-.085
5	-.096	-.170	.005	-.041	-.344	-1.003	.015	-.098	.017	-.086
10	-.143	-.171	.005	-.042	-.290	-0.978	.018	-.097	.019	-.085
20	-.124	-.158	.005	-.042	-.196	-0.949	.020	-.098	.022	-.083

Figure 11. Hand recorded stability output

After elimination of mill 2, due to electrical problems, It was determined that mill #1 was the least stable and mill #4 was the most stable.

None of these mills, however, showed sufficient stability to be used effectively in long-term tests or to maintain true calibration. An investigation into the potential cause of the instabilities was, therefore, started.

The first thing examined was the relationship between motor speed, as measured by the chopper blade frequency, and sensor output under constant applied field. Comparisons were made of chopper frequency versus mill output using both voltage and current regulated inputs to the chopper blade motor. A set of measurements using a voltage regulator is shown in Figure 12, while measurements made with a current regulator are shown in Figure 13. While the voltage regulator seemed to be more effective in maintaining a constant motor speed, neither of these tests showed any discernible relationship between motor speed (as measured by chopper frequency), shown in the top row of plots, and mean sensor output, shown in corresponding plots in the bottom row of each illustration.

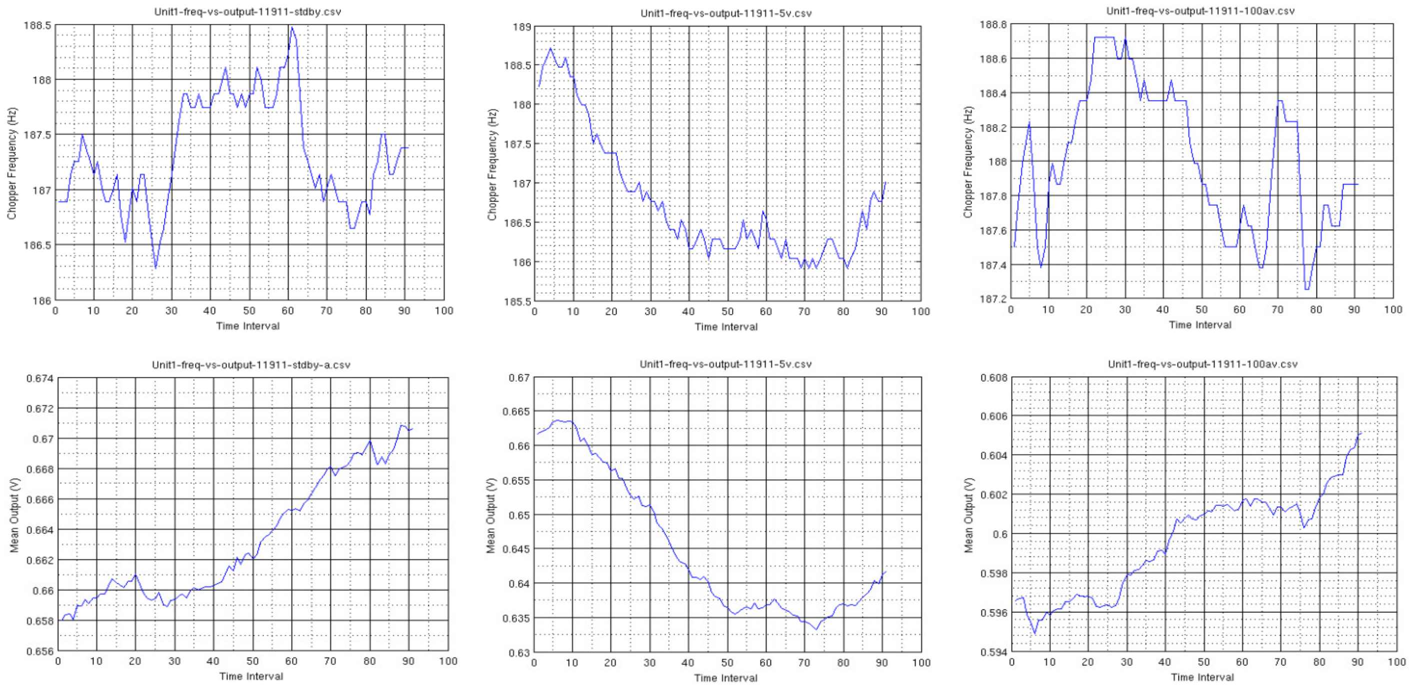

Figure 12. Comparison of chopper frequency and mill output using voltage regulator

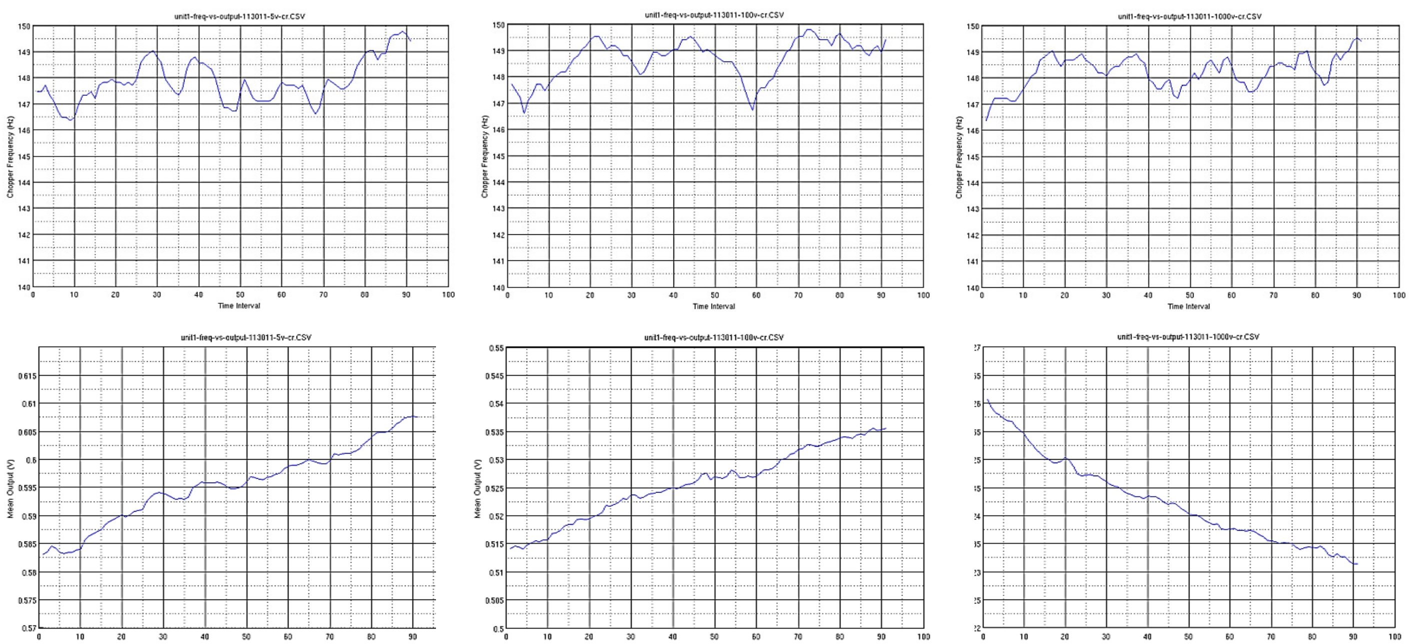

Figure 13. Comparison of chopper frequency and mill output using current regulator

All the mill output plots show slow drifts in output over the period of the tests, 90 to 100 seconds.

A further experiment was performed to determine if the instability was in the circuitry. The chopper blade signal was bypassed and signals were directly injected just beyond the sensor plates. Results of this test were exceptionally stable, varying only slightly about a common mean, over the 90 second test period.

A thorough check of the experimental setup and the circuitry was undertaken by the SSRC mentor at this point. It was determined that a common ground was lacking between the field mill and the calibration system. While the need for a common ground may seem obvious to experienced experimenters, student mentees should not be expected to understand this need. It illustrates the need to very clearly and concisely describe all components of testing and operations.

A comparison of mill output as a function of time with a common ground, Figure 14, shows the greatly improved stability given by the corrected calibration setup.

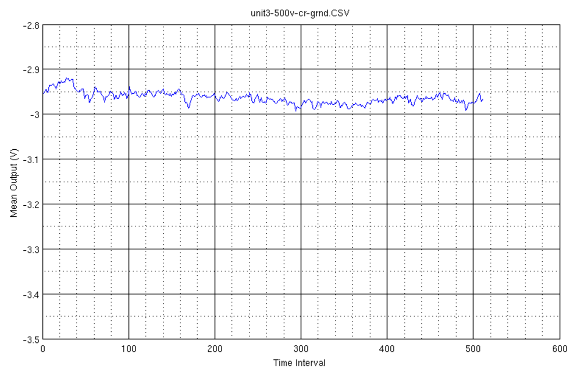

Figure 14. Stability output with common grounding

8.2 **Calibration Tests**

Four of the latest mills were calibrated over applied field values of +/- 10kVm^{-1}. All units produced very linear and repeatable results. The precision of the mills measurement capability was on the order of +/- 50Vm^{-1}.

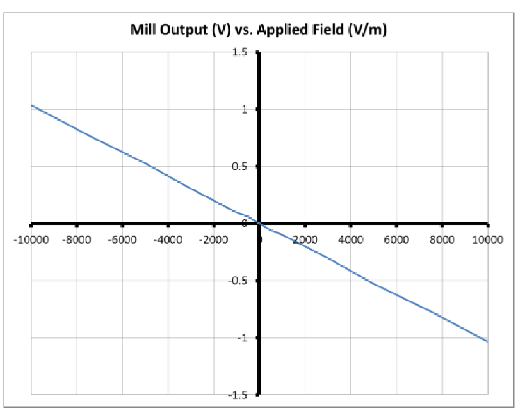

Figure 15. Typical beta mill calibration

8.3 **Side by Side Roof Top Test**

After calibration of the improved beta units, a side-by-side test was performed on the roof of the SSRC. The output of the Vaisala mill was again compared to the output of student mills. In this experiment, two student mills were deployed, one inverted in its “normal” weather protected position and one with its sensor plates exposed flush to a ground plate.

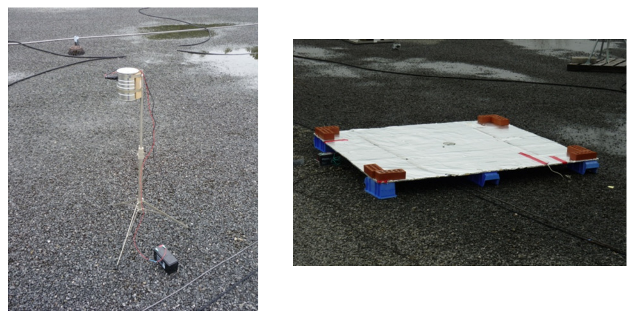

Figure 16. Side-by-side roof test. Student mill in inverted position (left) and with ground plane (right)

Unfortunately, the inverted mill malfunctioned and the only valid data was obtained from the mill in the ground plane. A comparison of the Vaisala and student mill output shows that the student mill tracked even these small, fair weather changes very well.

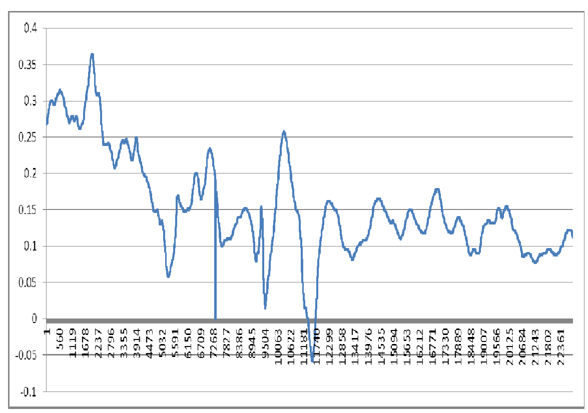

Figure 17. Vaisala output from side-by-side test

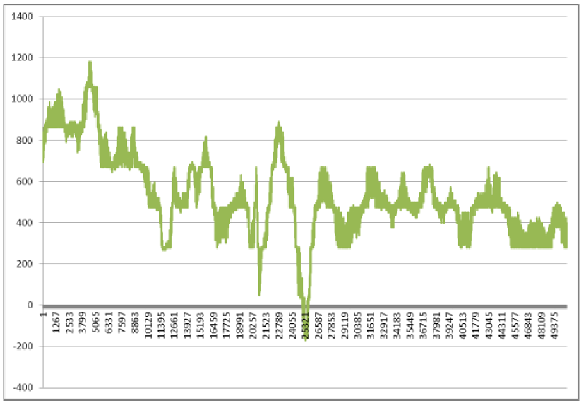

Figure 18. Student mill output from side-by-side test

Current Status and Future Work

A relatively simple design has been developed which can be reliably assembled and used by advanced high school students. This instrument has been shown to be in good agreement with a commercially available instrument.

Enhancement factors arising from the inverted "weather protected" orientation still need to be determined. The unit stability and reliability over extended periods of time also need to be established. Some improvements in the electrical design of the mills are also desired, such as including gain, offset and timing control circuitry. A reliable, yet simple data acquisition framework also needs to be established.

When these improvements have been achieved, the mills may be distributed and built by high schools across north Georgia and assembled into a cooperative monitoring network.

References

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